Interaction between a fast rotating sunspot and ephemeral regions associated with the major solar event on 2006 December 13

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ABSTRACT

The major solar event on 2006 December 13 is characterized by the approximately simultaneous occurrence of a heap of hot ejecta, a great two-ribbon flare and an extended Earth-directed coronal mass ejection. We examine the magnetic field and sunspot evolution in active region NOAA AR 10930, the source region of the event, while it transited the solar disk centre from Dec. 10 to Dec. 13. We find that the obvious changes in the active region associated with the event are the development of magnetic shear, the appearance of ephemeral regions and fast rotation of a smaller sunspot. Around the area of the magnetic neutral line of the active region, interaction between the fast rotating sunspot and the ephemeral regions triggers continual brightening and finally the major flare. It is indicative that only after the sunspot rotates up to 200° does the major event take place. The sunspot rotates at least 240° about its centre, the largest sunspot rotation angle which has been reported.

Subject headings: Sun: photospheric motions —Sun: magnetic fields —Sun: activity —Sun: flares

1. INTRODUCTION

Solar flares are powered by the energy stored in the stressed magnetic field, strong flares tend to occur in the vicinity of magnetic neutral lines where the field gradients are strong and the horizontal components are highly sheared (e.g., Harvey & Harvey 1976; Wang et al. 1994, 2002; Deng et al. 2006). The movement of magnetic footpoints by photospheric flows can lead to the destabilization of the magnetic field and hence to flares by increasing the length of the field lines in the corona (e.g., Somov et al. 2002). On the other hand, Nindos & Zhang (2002) have pointed out that shearing motions have little effect in

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the process of build-up of magnetic free energy that leads to the initiation of coronal mass ejections (CMEs).

Observations indicate that reconnection-favored emerging flux has a strong correlation with flare onset and CMEs (Schmieder et al. 1997; Ishii, Kurokawa & Takeuchi 1998; Kusano et al. 2002; Kurokawa, Wang & Ishii 2002; Sakajiri et al. 2004). Based on the flux rope model, an emerging flux trigger mechanism is proposed for the onset of CMEs, using two-dimensional magnetohydrodynamic (MHD) numerical simulations (Chen & Shibata 2000).

Besides magnetic field observations in active regions, white-light observations, furthermore, have shown sunspot evolution, e.g. sunspot rotation (Evershed 1910; Maltby 1964; Gopasyuk 1965). Stenflo (1969) has suggested that sunspot rotation may be involved with energy build-up and later release by a flare. With the high spatial and temporal resolution of recent satellite-borne telescopes, the observations of rotating sunspots and other magnetic structures have become more frequent and easier to identify (Nightingale et al. 2000, 2002; Brown et al. 2001). The sigmoid structures (Canfield & Pevtsov 1999), which are thought to be more likely to erupt and cause flares and CMEs, may be associated with the rotation of the magnetic footpoints in the photosphere. Brown et al. (2003) have shown that some sunspots rotate up to 200° about their umbral centre, and the corresponding loops in the coronal fan twist and erupt as flares.

The major event on 2006 December 13 exhibits almost simultaneous plasma ejecta, flare activity and a CME. It provides a good opportunity to study the surface magnetic activity and sunspot kinematics that results in the rather global magnetic instability. In this Letter, we examine the magnetic evolution and sunspot rotation prior to and during the course of the major event with the emphasis on the interaction of a rotating sunspot and ephemeral regions that characterizes this CME-producing active region.

2. OBSERVATIONS

Active region NOAA AR 10930 displayed the evolution of the complex magnetic structure, surrounded by many small dark pores and bright magnetic faculae, as observed by the *SOHO*/ MDI (Scherrer et al. 1995) and the Transition Region and Coronal Explorer (*TRACE*, Handy et al. 1999) over a 12-day interval from 2006 December 6 to December 18. The data set analyzed consists of four-day (from Dec. 10 to 13) full-disk magnetograms obtained from MDI, synchronous high-resolution white-light and UV (1600 Å) observations from the *TRACE* satellite, with spatial resolution of $1.0''$, temporal resolution of 20 - 60 s,

and field-of-view of $384'' \times 384''$. Fig. 1 shows general appearance of the active region NOAA AR 10930 in the decaying phase of the major flare.

3. CONCLUSIONS AND DISCUSSIONS

By checking the MDI and *TRACE* data, we notice that the first obvious magnetic evolution is the developing of magnetic shear. Fig. 2 presents the time sequence of the MDI longitudinal magnetograms (left), the corresponding *TRACE* continuum images (middle) and the corresponding *TRACE* 1600 Å images (right). Two contours in the continuum images at Dec. 10, 12:50 UT and 22:30 UT outline a dark thread, which connects the pair of opposite polarity sunspots of the active region. These contours are overplotted onto the corresponding longitudinal magnetograms and *TRACE* 1600 Å images. Before Dec. 10, 12:51 UT, the thread connects directly with the two sunspots. Ten hours later, although the thread still joins the two sunspots, its shape changes from beeline to reverse S-shape curve. Gradually the thread disappears and some new threads appear along the neutral line of the two sunspots (see the dash curves on the continuum image in the low panel). From the MDI magnetogram on Dec. 11 at 12:51 UT, we find that these new threads seem to be arch filament systems connecting the opposite polarities of ephemeral regions (ERs) which emerge along the sunspot neutral line. Fig. 3 clearly shows an ER (denoted by two pairs of arrows) on high resolution MDI magnetograms, after the magnetic shear of the active region is well developed. Firstly the two magnetic elements belonging to the ER are ellipses in shape, and separate each other with a speed of 0.5 km s^{-1}. After four-hour evolution, the shape of the elements looks like two narrow ribbons along the neutral line of the active region, as the ER is squeezed tightly by the region. In the process of the ER appearing, multiple neutral lines (marked by dark lines in the 02:40 UT magnetogram) develop, and continuous UV brightening appears in the area of these neutral lines.

We have noticed that ERs appear not only prior to the onset of the major solar event, but also during the course of the event. Fig. 4 shows an ER appearing during the flare/CME event. The arrows point to the ER. The positive element of the ER plunges into the neutral line area of the active region. Before it merges to the positive polarity magnetic field of the active region, it cancels with surrounding opposite polarity field, meanwhile UV brightening appears. The bright material ejects along the axis of the ER to the right (shown by the arrow in the *TRACE* 1600 Å image at 01:40 UT). Twenty minutes later, the major flare takes place. The negative element moves away from the active region with a speed of 0.5 km s^{-1}. At 06:05 UT, the distance between the two elements is about 22,000 km, and an UV bright ribbon connects with the two elements of the ER.

Observations from *TRACE* in the photospheric white-light channel have shown that, from the end of Dec. 10 on, sunspot rotation in the active region accompanies the magnetic flux emergence in the form of ERs in the neutral line area. Fig. 5 shows an example of the rotation of a dark penumbral feature 'f3' (marked by the arrows). The feature firstly appeared near Dec. 12, 00:10 UT, it rotated around the centre (shown by smaller circles) of the smaller spot. From Dec. 12, 00:10 UT to 20:50 UT, the dark feature rotated about 190°, and the mean angular speed reaches 9° hr^{-1}. In the following 14 hr, the feature became larger and larger, due to the converging of other unresolved features. The angular speed decreased to 2° hr^{-1} on average. Finally the dark feature broke up and gradually decayed. By checking the continuum data, we can clearly identify that in the penumbra of the smaller sunspot, there are several dark features which rotated around the spot. Fig. 6 shows the rotation of the three penumbral features mentioned in Fig. 5. It shows that a penumbral feature started to rotate while the shear developed, and the rotational speed is about 20° hr^{-1}. Between 02:00 UT and 12:00 UT on Dec. 12, the rotational speed of all the three features is low with a mean value of 4° hr^{-1}. Several hours prior to the flaring activity, all the three features underwent fast rotational process (see the small circles in the bottom panel). Before the flare took place, the rotational angle of each feature exceeded 200°. During the course of the flaring activity, these features displayed a relatively low rotational speed. After the onset of the flaring activity, these features continuously rotated around the sunspot with a mean speed of 2° hr^{-1}. Near the end of Dec. 13, the amount of the rotational angle for each feature was around 240°. This is the largest angle which has been reported.

The major solar event manifests itself as a heap of bright ejecta, a great flare, and an extended Earth-directed CME. For such a major event, the obvious activities in its source region are the development of magnetic shear, the appearance of ephemeral regions and fast rotation of a sunspot. More importantly, the major event takes place only after the rotational angle of the sunspot reached 200°. It is prefigurative that the interaction between ephemeral regions and fast rotation of a sunspot plays a decisive role in producing the global instability responsible for this major solar event.

Régnier & Canfield (2006) have identified that in active region NOAA AR 8210, a fast motion of an emerging polarity is associated with small-scale reconnections, and a sunspot rotation enables the occurrence of flare by a reconnection process close to a magnetic surface. Wang & Shi (1993) presented a two-step reconnection scenario for flare process. The first step of reconnection is seen as flux cancellation observed in the photosphere (Zhang et al. 2001). This reconnection transports the magnetic energy and complexity into coronal magnetic structure. The second step of reconnection is directly responsible for transient solar activities, and takes place only when some critical status is achieved in the corona.

By performing MHD simulations in which the twisting motions are included, several authors (e.g., Mikić, Schnack & Van Hoven 1990; Galsgaard & Nordlund 1997) have reported that photospheric flows will drive the loop unstable to the ideal kink instability after the average twist exceeds a critical value of 450°. Later, Gerrard et al. (2003) have simulated the rotation of a pore around a sunspot. While the pore rotates 180° around the sunspot, the current increases rapidly as the centre of the pore makes contact with the large sunspot. This current build-up could be an explanation of an observed flaring. Observational result in this Letter (e.g., see Fig. 6) is consistent with the simulation of Gerrard et al. (2003).

We are keenly aware of the limitations imposed by the comparatively low spatial resolution of MDI magnetograms. Future observations at higher spatial resolution are likely to uncover the nature of the source regions of major solar events. A detailed study of this flare/CME event is planned with Hinode data.

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Fig. 1.— General appearance of the active region NOAA AR 10930 on different wavelength in the decaying phase of the major flare. *Upper left:* an MDI longitudinal magnetogram. The window outlines a subarea where ephemeral regions appear (see Fig. 4); *Lower left:* A continuum intensity image from *TRACE*. 'N1' is the main sunspot of the active region, 'P1' and 'P2' are the following sunspots. The window denotes the field-of-view of Fig. 5 where the sunspot 'P1' fast rotates; *Upper right:* a *TRACE* 1600 Å image showing the two ribbons ('R1' and 'R2') of the flare; *Lower right:* a *TRACE* 195 Å image showing the post-flare loops. The field-of-view is about $100'' \times 100''$.

Fig. 2.— The time sequence of the MDI longitudinal magnetograms (the left column), the corresponding *TRACE* continuum images (the middle column) and the corresponding *TRACE* 1600 Å images (the right column), showing the developing of magnetic shear. The field-of-view is about $50'' \times 50''$. The dotted contours and curves are described in the text.

Fig. 3.— Time sequence of the high resolution MDI longitudinal magnetograms, showing the emergence flux appeared near the magnetic neutral line of the active region, after the AR 10930 magnetic shear is well developed. The field-of-view is about $60'' \times 60''$. The arrows and the dark lines are described in the text.

Fig. 4.— Time sequence of the MDI longitudinal magnetograms (the left column), the corresponding *TRACE* continuum images (the middle column) and the corresponding *TRACE* 1600 Å images (the right column), showing the appearance of bipolar magnetic features during the course of the major flare/CME event. The field-of-view is about $50'' \times 50''$. The arrows are described in the text.

Fig. 5.— Time sequence of *TRACE* continuum images showing the rotation of a dark penumbral feature ('f3') around the centre (marked by small circles) of 'P1' mentioned in Fig. 1. 'f1' and 'f2' are other two rotating dark features which appear prior to the emergence of 'f3'. The three arrows in the continuum image at Dec. 12, 09:12 UT point to the three features ('f1', 'f2' and 'f3'), otherwise the arrows points to 'f3'. The convergence of 'f1', 'f2' and other unresolved features forms 'P2' (see Fig. 1). The two solid lines in the first and last images connect 'f3' with the centre-of-gravity of 'P1', and the dotted line in the last image is a duplicate of the solid line in the first image. The field-of-view is about $40'' \times 40''$.

Fig. 6.— Plots showing rotational angle (top) of the three penumbral features ('f1', 'f2' and 'f3' shown in Fig. 5) and rotational speed (bottom) of the corresponding features versus time. Dark gray area represents the shear developing period, and light gray area the flaring activity period. The minus rotation of these features is caused by their moving away from the sunspot.